THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 53, No. 7, September 1974
Printed in U.S.A.

Low-Noise, Integrated, Millimeter-Wave Receiver

By B. GLANCE and W. W. SNELL, JR.

(Manuscript received December 7, 1973)

A low-noise, hybrid-integrated, millimeter-wave receiver that consists of a local oscillator and a downconverter on a silica substrate is described in this paper. The source for the local oscillator is a Gunn diode, and the mixer element is a beam-leaded Schottky barrier diode. A novel filter circuit is used to combine the local oscillator and the signal with low insertion loss in the signal path. The single-sideband noise figure of the receiver at 30 GHz is 5.5 dB, including 0.8-dB contribution of the if amplifier, and the rms FM frequency variation resulting from the local oscillator is 168 $Hz/\sqrt{KHz}$.

I. INTRODUCTION

Large numbers of solid-state, low-noise receivers that can be built into compact low-cost radio transmission systems are needed for future terrestrial and satellite communication systems. This paper describes a low-noise microstrip receiver with a single-sideband noise figure of 5.5 dB at 30 GHz, including 0.8 dB resulting from the if amplifier. The receiver consists of a Gunn diode, a Schottky barrier device, and a microstrip conductor pattern on a fused-quartz substrate. The circuit is fabricated using thin-film photolithographic processing techniques. It can be readily scaled to frequencies up to 100 GHz.

II. RECEIVER DESCRIPTION

The microstrip circuit pattern consists of a 2-μm-thick evaporated chromium-gold film on a silica substrate, as shown in Fig. 1. It includes an input rf filter, a pump filter, a low-pass if filter, and a Gunn oscillator with a biasing circuit. The pump and rf signal filters are made from a single rectangular resonator that supports two orthogonally polarized microstrip modes.[1] The resonance for the pump

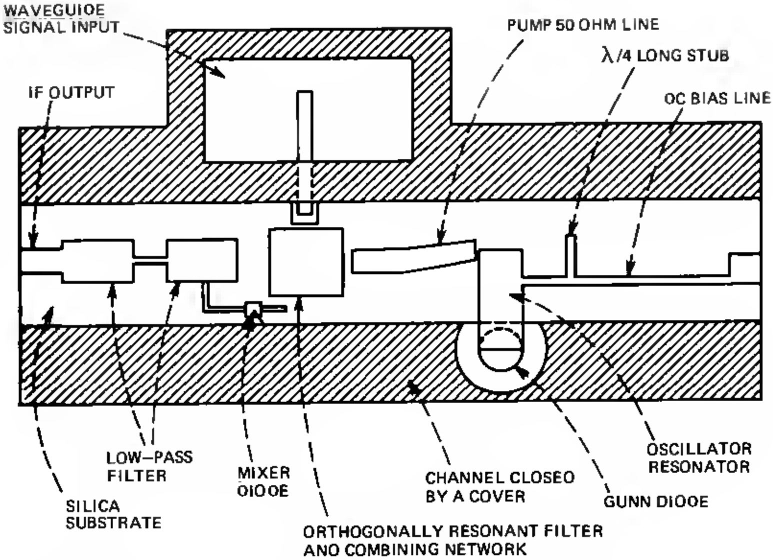

Fig. 1—Schematic drawing of the microstrip receiver circuit in a rectangular channel with a length of 25.4 mm, a width of 4.0 mm, and a depth of 2.5 mm. The silica substrate thickness is 0.34 mm.

signal is directed along the channel, with the resonance for the input signal in the perpendicular direction. Each orthogonal resonance has the response of a single-pole filter. Isolation between the signal and pump ports is >20 dB, which is equal to or better than the isolation normally achieved in a balanced downconverter design. A single beam-leaded Schottky barrier diode (see Table I) is used for downconverting the rf signal to the if frequency. The diode is shunt-mounted to a

Table I — Gunn diode and mixer diode parameters

Diodes	Parameters	
Gunn diode Microwave Associates Model No. MA49173	Frequency Maximum output power dc bias voltage dc bias current	28–30 GHz 50 mW 5 volts 800 mA
Mixer diode Hewlett-Packard Model SO82-2716	Junction resistance Series resistance Junction capacitance Package inductance Package capacitance	120 ohms 10 ohms 0.07 pF 0.1 nH 0.07 pF

high-impedance microstrip line. The length of this line was chosen so that the reactance seen by the diode at the image frequency is optimized to obtain a low noise figure.

A Gunn diode connected to a microstrip resonator provides the pump power at 28.4 GHz. The diode is inserted into the side wall of the rectangular channel that supports the substrate (Fig. 1). The microstrip resonator is coupled capacitively to a 50-ohm line that feeds the pump signal into the orthogonally resonant filter. Direct-current bias to the Gunn diode is provided through a high-impedance line connected to the microstrip resonator at an rf minimum. Radio-frequency leakage is further minimized in the bias line by means of a $\lambda/4$-long microstrip stub. The metallized substrate is mounted in a closed rectangular channel to eliminate radiation losses and parasitic coupling to external circuits. Waveguide modes inside the channel are below cut-off for the frequency range of the receiver. The Gunn diode (see Table I), encapsulated in a ceramic pill package, gives up to 50 mW at 30 GHz. The oscillator frequency can be tuned from 27 to 29 GHz. The tuning mechanism consists of a small piece of dielectric material attached to a nylon screw that is inserted in the channel above the microstrip resonator. The adjustable dielectric loads the fringe field of the resonator and provides a means for tuning the local oscillator frequency. Figure 2 shows the 30-GHz microstrip receiver and Table I lists the Gunn diode and the mixer diode parameters.

III. NOISE FIGURE MEASUREMENT

The overall mixer noise figure of a receiver is[2]

$$F_o = L_c(N_r - 1 + F_{i-f}), \tag{1}$$

where L_c is the downconverter conversion loss, N_r is the mixer diode noise ratio,[2] and F_{i-f} is the noise figure of the if preamplifier.

The parameter N_r can be obtained by measuring the system noise figure at constant diode current, with two if preamplifiers with different noise figures $(F_{i-f})_1$ and $(F_{i-f})_2$. If $(F_o)_1$ and $(F_o)_2$ are the two measured system noise figures, the parameter N_r is given by

$$N_r = \frac{(F_o)_2(F_{i-f})_1 - (F_s)_1(F_{i-f})_2}{(F_o)_1 - (F_o)_2} + 1. \tag{2}$$

The system noise figure was measured by using a wideband preamplifier with a noise figure of 4.5 dB yielding a total noise figure of 9.2 dB. Measurements were also made with a low-noise parametric amplifier with a noise figure of 0.8 dB, giving in this case a system noise figure of

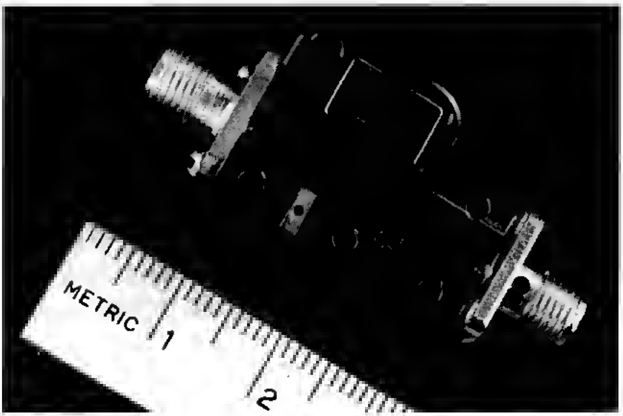

Fig. 2—The receiver. A probe that extends into an adjacent RG-96/U waveguide is used to couple to the signal.

5.5 dB. Substituting these values into eq. (2) gives a figure of merit equal to 1, as expected from a good mixer diode.[2] Equation (1) then becomes

$$F_o = L_c \times F_{i-f}, \tag{3}$$

yielding a downconverter noise figure equal to the mixer conversion loss. Thus,

$$L_c = 4.7 \text{ dB}. \tag{4}$$

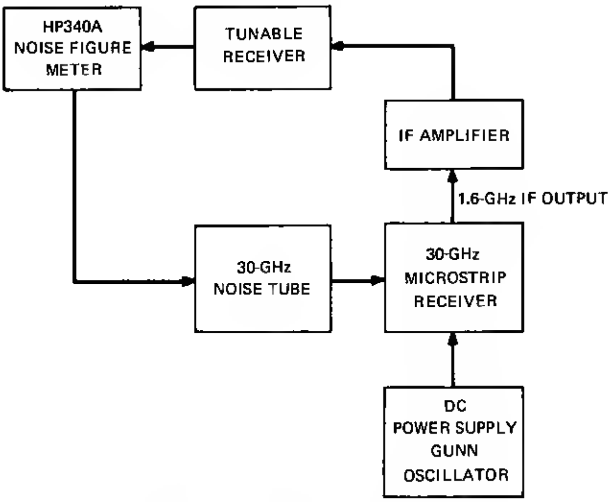

Fig. 3—Noise figure measurement setup.

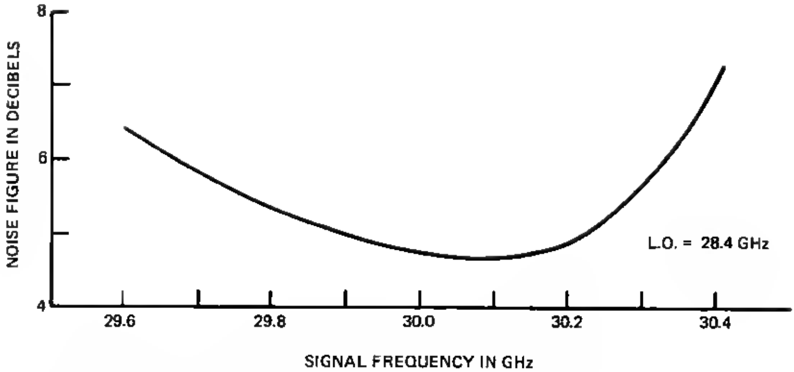

Fig. 4—Measured noise figure vs frequency of the rf receiver, not including the if amplifier contribution.

Figure 3 is a schematic diagram of the noise measuring setup. The signal frequency is 30 GHz, the pump frequency is 28.4 GHz, the if frequency is 1.6 GHz, and the handwidth is 460 MHz wide at the -1 dB points. Figure 4 shows the single-sidehand noise figure of the downconverter, not including the if contribution.

IV. FM NOISE MEASUREMENT

FM noise resulting from the local oscillator is an important parameter in downconverters designed for receiving angle modulated signals, since the FM noise of the local oscillator is directly added to the phase information contained in the downconverted if signal.

Measurement of the FM noise was made hy heating the pump frequency with a 30-GHz low-noise signal. Figure 5 shows the power spectral density measured at 1.64 GHz with a 100-Hz wide filter and a scanning time of 2 seconds per division. The Lorentzian shape of the observed power spectrum is characteristic of an oscillator with white gaussian noise. Theoretical analysis for this type of oscillator shows that the spectral density around the carrier is mainly due to FM noise and varies as[3–5]

$$S_{\rm FM}(f) = \frac{\omega_o^2 kT}{2Q^2} \times \frac{1}{(\omega_o^2 kT/4Q^2P_o)^2 + (\omega - \omega_o)^2}, \tag{5}$$

where

ω_o = oscillator frequency

P_o = output power

and

Q = oscillator external loaded Q.

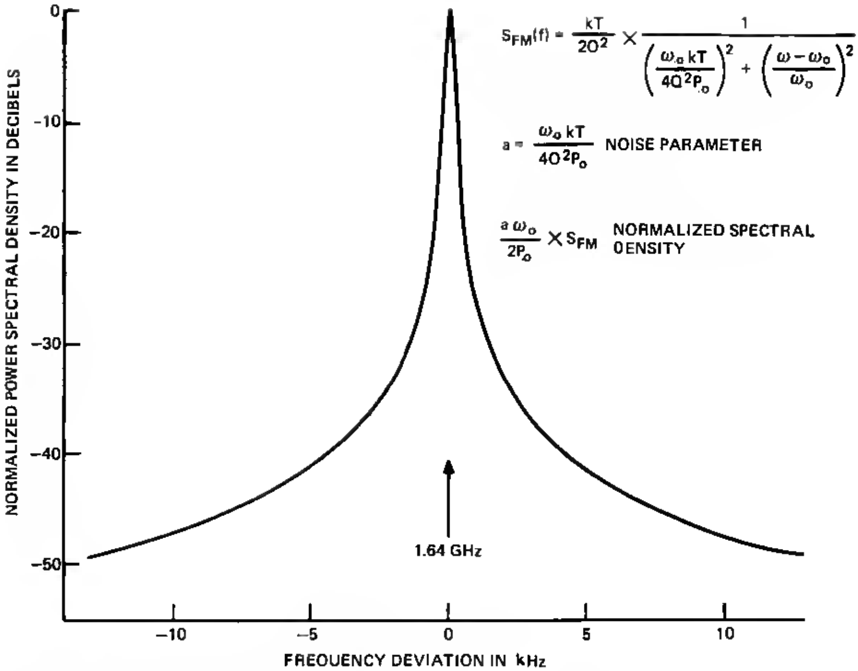

Fig. 5—Measured power spectral density of the local oscillator signal downconverted at the if frequency.

Equation (5) normalized to unity varies as

$$y = \frac{a^2}{a^2 + x^2}, \tag{6}$$

where a is the noise parameter given by

$$a = \frac{\omega_o kT}{4Q^2P_o} \tag{7}$$

and

$$x = \frac{\omega - \omega_o}{\omega_o} \tag{8}$$

$$y = S(f)_{\mathrm{FM}} \times \frac{a\omega_o}{2P_o}. \tag{9}$$

The noise parameter a is obtained from the measured power spectrum (shown in Fig. 5) by using eq. (6). Figure 6 shows the values determined for the parameter a for various frequency deviations. The results

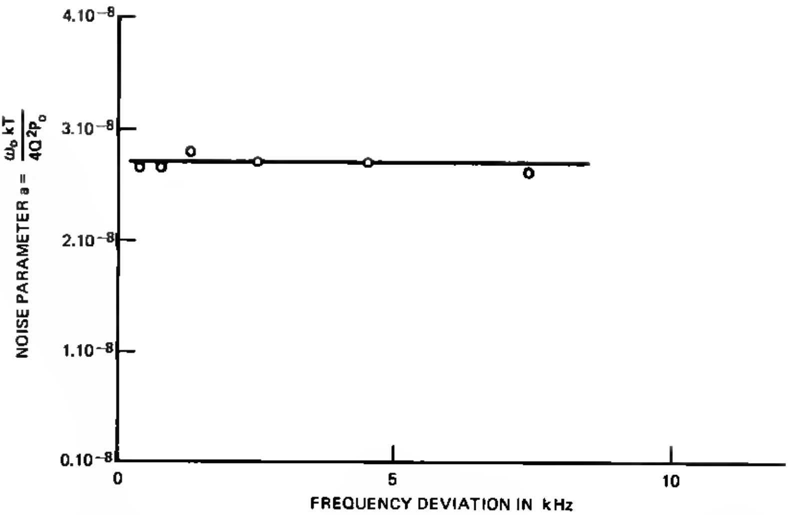

Fig. 6—Calculated values of the noise parameter $a = \omega_o kT/4Q^2P_o$ vs frequency deviation.

are distributed, within the error margin of our measurements, around a constant value of

$$\langle a \rangle = 2.7 \times 10^{-8}. \tag{10}$$

This is a good experimental verification that the noise in the signal is in fact mainly FM in character as predicted by eq. 5.

The rms FM frequency deviation per $\sqrt{\text{Hz}}$ is given by[4]

$$\Delta\omega_{\text{rms}} = \frac{\omega_o}{Q}\sqrt{\frac{kT}{P_o}}, \tag{11}$$

which can be written from eq. (7) as

$$\Delta\omega_{\text{rms}} = 2\omega_o\sqrt{\frac{a}{\omega_o}}. \tag{12}$$

Substituting eq. (10) into eq. (12), the rms FM frequency deviation becomes

$$\Delta f_{\text{rms}} = 168\,\frac{\text{Hz}}{\sqrt{\text{KHz}}}. \tag{13}$$

The receiver described in this paper was designed for use in a PCM system in which the phase of the carrier will be modulated between four levels with a sampling period $T = 7.3$ ns, which will occupy a

bandwidth $B = 200$ MHz. The rms phase deviation resulting from the local oscillator, which occurs in the time interval T, is

$$\Delta\phi_{\text{rms}} = 2\pi\Delta f_{\text{rms}} T\sqrt{B}. \tag{14}$$

The rms phase fluctuation calculated from eq. (13) equals

$$\Delta\phi_{\text{rms}} = 0.2°. \tag{15}$$

Equation (15) shows that the noise due to the local oscillator is an insignificant contrihution to the modulated signal.

V. CONCLUSION

A low-noise hyhrid integrated receiver that is comparahle to the hest conventional waveguide circuits[6] has heen huilt and tested at 30 GHz. A unique orthogonal resonator input circuit allows the use of a single mixer diode resulting in a performance comparable to conventional halanced downconverter receivers. The receiver circuit, made on a single silica suhstrate, can he mass-produced with high reliahility. It can he readily scaled to higher frequencies and is especially suited for incorporation into millimeter-wave communication systems.

VI. ACKNOWLEDGMENTS

The authors wish to thank M. V. Schneider for his helpful comments and many discussions. The expert assistance of E. Zack and K. Schwarz in huilding advanced circuits is also gratefully acknowledged.

REFERENCES

1. W. W. Snell, "Microstrip Downconverter from 30 GHz to 1.5 GHz," unpublished work.
2. H. A. Watson, ed., *Microwave Semiconductor Devices and Their Circuit Applications*, New York: McGraw-Hill, 1969, pp. 387, 389.
3. W. A. Edson, "Noise in Oscillators," Proc. IRE, *48* (August 1960), pp. 1454–1466.
4. K. Kurokawa, "Noise in Synchronized Oscillators," IEEE Trans. on Microwave Theory Tech., *MTT-16*, No. 4 (April 1968), pp. 234–240.
5. J. Josenhans, "Noise Spectra of Read Diode and Gunn Oscillators," Proc. IEEE, *54*, No. 10 (October 1966), pp. 1478–1479.
6. M. Viggh, "Low Noise Receivers for Millimeter Wave Signals," Proc. 1971 European Microwave Conference, Vol. 1, pages A11/1:1, A11/1:4.